Published online March 29, 2006

Dairy Diet Impacts on Fecal Chemical Properties and Nitrogen Cycling in Soils

J. M. Powell,* M. A. Wattiaux, G. A. Broderick, V. R. Moreira, and M. D. Casler

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

ABSTRACT

Availability of manure nitrogen (N) to crops is mitigated by many factors including manure type and composition. Whereas relationships between dairy diets, milk production, manure N excretion, and urine N losses as ammonia have been documented, very little information exists on how diets impact fecal carbon (C), N content, and partitioning, and how these factors impact fecal N mineralization and plant N uptake after application to soil. Feces from 24 to 63 dairy cows (*Bos taurus*) fed 14 typical diets were incubated aerobically in a sandy loam and two silt loam soils, and soil inorganic N (IN) was determined periodically during a 365-d period. Feces from 12 of the 14 diets were applied to the same soils and oat (*Avena sativa* L.), sorghum (*Sorghum bicolor* L. Moench), and sorghum ratoon dry matter (DM) and N uptake were determined over a 155-d period. Feces from cows fed alfalfa (*Medicago sativa* L.) silage (AS)-based diets generally lead to higher soil IN levels than soils amended with feces from corn (*Zea mays* L.) silage (CS)-based diets, especially in soils amended with feces from CS-low crude protein (LCP) diets; feces from AS-based diets increased plant DM and N uptake; after application to a silt loam, feces from high crude protein (HCP) diets resulted in greater soil IN levels than feces from LCP diets; and feces from LCP diets did not impact soil IN but decreased plant DM and N uptake. Carbon to N (C/N) ratios of applied feces were found to be significant predictors of plant DM and N uptake. There appears to be a range of dietary options that satisfy nutritional requirements of high-producing dairy cows and produce feces having differential effects on soil N mineralization and plant N uptake after application to soil.

Dairy cows and replacement heifers in the Midwest and Northeast regions of the USA are fed primarily homegrown feed from crop rotations comprising alfalfa, corn, oats and soybean (*Glycine max* L. Merr.), and protein and mineral supplements are purchased to balance dairy rations. To remain economically viable, many farms are increasing herd size and replacing alfalfa with CS in crop rotations. Much alfalfa protein is degraded in the silo and rumen, impairing protein utilization and milk production unless more costly rumen undegraded protein supplements are fed. Such supplementation increases the cost of milk production, manure N excretion, and N loss from farmland. Substitution of most dietary alfalfa with CS and soybeans reduces excessive protein breakdown in the rumen, manure N excretion by livestock, and the cost of milk production.

Dairy cows utilize feed N much more efficiently than many other ruminant livestock, but under current feeding practices, only 20 to 30% of the crude protein (CP) (N × 6.25) fed to dairy cows is secreted in milk. An average cow annually producing 8200 kg of milk also excretes 21 000 kg of manure containing about 110 kg N (Van Horn et al., 1996). Under current common feeding practices for lactating cows fed in confinement in the Midwest and Northeast USA, N not secreted in milk is excreted about equally in feces and urine, but this can be affected dramatically by diet (Broderick, 2003; Wattiaux and Karg, 2004a). Fecal N can be divided into two general pools: (1) endogenous N consisting of microbial products and microorganisms from the rumen, the intestine, and the hind gut, and the N originating from the digestive tract itself; and (2) undigested feed N (Mason and Frederiksen, 1979). For ruminant livestock, fecal N partitioning can be influenced highly by diet (Somda et al., 1995). Whereas rumen microbial products and other endogenous, organic N forms in feces make a significant contribution to crop N requirements the year following manure application, undigested feed N in feces mineralizes slowly in soil, and is therefore unavailable to plants over the short-term (Sørensen et al., 1994; Somda et al., 1995; Powell et al., 1999). After having already passed through the digestive track of livestock, the undigested feed N component of feces is relatively recalcitrant in soils.

Much recent knowledge has been generated about relationships between dietary phosphorus (P), cow performance, the amount and form of P excreted in manure, and its environmental impacts (Satter et al., 2005). Relatively little is known, however, about relationships between the type and amount of forage and CP fed to dairy cows, manure N composition, and cycling in soils. In an effort to examine relationship between dairy feed and manure N mineralization, Van Kessel and Reeves (2002) incubated unfed dairy diet components with soil and tracked soil IN. In a study with sheep (*Ovis aries* L.), however, Powell et al. (1999) found that unfed diet components and feces derived from the same feed components have very different physical and chemical characteristics, which after application to soil, impact plant yield and N uptake. In a more recent study, Sørensen et al. (2003) determined positive relationships between dietary CP, and negative relationships between dietary neutral detergent fiber (NDF) and mineralization of N contained in slurry from dairy cows fed various diets. These dairy diets fed in Europe, however, comprised forages and supplements which differ considerably from what is fed to dairy cows in confinement operations of the USA. To test an overall hypothesis that diets impact

J.M. Powell, G.A. Broderick, and M.D. Casler, USDA-ARS U.S. Dairy Forage Research Center, Madison, WI 53706; M.A. Wattiaux, Dep. Dairy Science, Univ. of Wisconsin, Madison, WI 53706; V.R. Moreira, Louisiana State Univ. Agric. Center Southeast Research Station, Franklinton, LA 70438. Received 30 Aug. 2005. *Corresponding author (jmpowel2@wisc.edu).

Published in Soil Sci. Soc. Am. J. 70:786–794 (2006).
Soil Fertility & Plant Nutrition, Nutrient Management & Soil & Plant Analysis, Landscape Management
doi:10.2136/sssaj2005.0286
© Soil Science Society of America
677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: AH, alfalfa hay; AS, alfalfa silage; C/N, carbon to nitrogen ratio; CS, corn silage; CP, crude protein; DM, dry matter; F, fiber; HCP, high crude protein; HF, high fiber; IN, inorganic nitrogen; LCP, low crude protein; LF, low fiber; MF, medium fiber; NDF, neutral detergent fiber.

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

Table 1. Soil designations and properties used in incubation and greenhouse trials.

Soil designations		Collection location	Sand	pH	Total C	Inorg C	Total N	Bray1 P
Series	Classification		%		g kg^{-1}			mg kg^{-1}
Loyal	Fine-loamy, mixed, superactive, frigid Oxyaquic Glossudalfs	44° 35′ N 90° 10′ W	13	7.0	26.1	2.6	2.12	42
Plano	Fine-silty, mixed, superactive, mesic, Typic Argiudolls	43° 15′ N 89° 30′ W	26	7.4	35.5	9.9	2.22	72
Roshott	Coatse-loamy, mixed, superactive, frigid, Haplic Glossudalfs	44° 15′ N 89° 05′ W	53	5.7	8.7	0.4	0.87	42

manure N cycling in soils, the objective of this study was to determine effects of typical dairy diets fed in the Midwest USA on the chemical composition of dairy cow feces and, after application to soil, effects of feces derived from different diets on soil IN levels, plant yield and N uptake.

MATERIALS AND METHODS

Soils Description

Representative soil samples were taken with a stainless steel shovel from the surface (0–20 cm) horizons of two silt loams (Loyal and Plano soils) and one sandy loam (Rosholt soil; Table 1). The soils were reported to have not received manure for at least the preceding 4 yr. Soil samples were air-dried, sieved to pass 2-mm screen, and stored in plastic containers until use in the incubation and greenhouse trials. Soil pH (1:1 water), total C, total N, and Bray 1 P were determined according to standard procedures at the Soil and Plant Analyses Lab, University of Wisconsin-Madison (SPALS, 2004).

Synopsis of Feeding Trials and Feces

Fresh fecal samples were taken directly from the rectum of dairy cows during three lactation trials that incorporated a wide range of forage and dietary CP levels (Table 2). One feeding trial (Broderick, 2003) used 63 cows to investigate interactive effects of dietary CP and neutral detergent fiber (F) on milk production and composition. In brief, three CP levels were obtained by replacing high-moisture corn with soybean meal: LCP of 15.1% dietary DM, MCP of 16.7%, and HCP of 18.4%. Each CP level was fed at three F levels obtained by manipulating dietary forage: low F (LF) of 28%, medium F (MF) of 32% and high F (HF) of 36%. Feces derived from six dietary CP-F combinations were selected for the incubation trial and feces from four dietary CP-F combinations were selected for the greenhouse trial (Table 3). A second feeding trial (Moreira et al., 1999) used 24 cows to compare cow responses to CS, alfalfa hay (AH), or AS. The forage/concentrate DM ratio of 50:50 was similar across diets. The forage component consisted of 100% CS, 75%CS–25%AH, 75%CS–25%AS, or 50%CS–50%AS. The third feeding trial (Wattiaux and Karg, 2004a) used 48 cows to evaluate cow responses to CS or AS as primary forage source, each fed at low LCP level of 16.7% or a HCP level of 17.8%. Diets were fed as total mixed rations comprised of 55% forage and 45% concentrate. The forage component comprised 25%CS–75%AS, or 75%CS–25%AS.

For all three feeding trials, fresh fecal samples were taken from the rectum of cows, pooled among cows fed similar diets, and subsamples frozen. Subsamples were thawed, oven dried (60°C) to a constant weight, and ground to pass a 2-mm sieve for use in the incubation and greenhouse trials. Subsamples were further ground to pass a 1-mm sieve; dried at 100°C, 24 h for DM determination; total C and total N in feces were determined on a VarioMax Elementar (Hanau, Germany); and fecal cell wall components were determined using the detergent system (Goering and Van Soest, 1970) as neutral detergent fiber (NDF). Total N contained in NDF was also determined on the VarioMax. The NDF insoluble N (NDIN) was deemed to be the undigested feed N component of feces (Mason and Frederiksen, 1979).

Soil Incubations

One hundred grams of air-dried soil were placed in 90-mL plastic urine sample cups, P was applied at the rate of 40 kg P ha^{-1} as KH_2PO_4, and distilled water was added to achieve soil moisture contents of approximately 50% water-filled pore space (WFPS). Each cup had a screw-on lid with 5 pinholes. After pre-incubation at 25°C for 1 wk, dried, ground feces from the 14 diets (Table 3) were applied to triplicate cups at a rate equivalent to 350 kg total N ha^{-1}, an agronomic rate assuming approximately 40% availability of applied fecal N. Feces were incorporated into soils by stirring with a spatula, and the soil-feces mixtures were repacked gently to natural bulk densities of approximately 1.20, 1.30, and 1.35 g cm^{-3} for the Loyal, Plano, and Rosholt soils, respectively. Triplicate unamended controls for each soil were also included. Soils were brought to 60% WFPS with distilled water, and cups were returned to incubation chambers. Moisture content was maintained at 60% WFPS throughout the trial by weighing cups and misting

Table 2. Synopsis of feeding trials from which dairy feces were derived.

Feeding trial description	Feeding trial designation	Designations used in this study: Feed components	Feed component description (DM basis)
Levels of crude protein (CP) and neutral detergent fiber (F) (Broderick, 2003)	CP-F	LCP-HF	Low CP (151 g kg^{-1}) with High Fiber (360 g kg^{-1})
		HCP-HF	High CP (184 g kg^{-1}) with High Fiber
		LCP-MF	Low CP with Medium Fiber (320 g kg^{-1})
		HCP-MF	High CP with Medium Fiber
		LCP-LF	Low CP with Low Fiber (280 g kg^{-1})
		HCP-LF	High CP with Low Fiber
Levels of corn silage (CS), alfalfa silage (AS) or alfalfa hay (AH) (Moreira et al., 1999)	CS-AS/AH	100CS	All forage dry matter (DM) was CS
		75CS-25AH	75% of forage DM was CS, 25% was alfalfa hay
		75CS-25AS	75% of forage DM was CS, 25% was alfalfa silage
		50CS-50AS	50% of forage DM was CS, 50% was alfalfa silage
CS- or AS-based diets at two levels of CP (Wattiaux and Karg, 2004b)	CS-AS-CP	CS-LP	Corn silage-based diet fed with low CP (167 g kg^{-1})
		CS-HP	Corn silage-based diet fed with high CP (178 g kg^{-1})
		AS-LP	Alfalfa silage-based diet fed with low CP
		AS-HP	Alfalfa silage-based diet fed with high CP

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

Table 3. Concentrations of total carbon (TC), total nitrogen (TN), neutral detergent fiber (NDF), undigested feed N (NDIN), and carbon/nitrogen (C/N) ratio of feces used in study.

Feeding trial designation†	Feed components	TC	TN	NDF	NDIN	C/N
		g kg DM^{-1}				g g DM^{-1}
CP-F	LCP-HF	451	27.0	571	6.5	17.8
	HCP-HF‡	447	29.4	564	7.3	14.7
	LCP-MF	462	27.6	538	6.6	16.0
	HCP-MF	453	29.4	599	7.8	16.5
	LCP-LF‡	457	28.6	526	6.6	11.7
	HCP-LF	460	30.5	512	5.6	14.5
CS-AS-AH	100CS	452	29.0	545	8.0	15.8
	75CS-25AH	461	30.3	528	7.8	16.1
	75CS-25AS	457	29.7	505	8.4	14.5
	50CS-50AS	474	32.2	501	7.6	15.0
CS-AS-CP	CS-LP	448	28.4	570	8.3	15.5
	CS-HP	454	28.2	537	6.4	14.8
	AS-LP	444	24.4	545	4.8	18.3
	AS-HP	439	24.4	561	5.3	18.1

† CP, crude protein; F, neutral detergent fiber; CS, corn silage; AS, alfalfa silage; AH, alfalfa hay.
‡ Not used in the greenhouse trial.

them with distilled water at intervals no longer than 3 d. Single cores were taken from cups using a 1.5-cm i.d. polyvinyl chloride (PVC) pipe at 7, 14, 28, 56, 112, 224 an 365 d after application. Cores were divided into approximately two equal sections, one was frozen and the other oven-dried at 105°C for 24 h to determine dry weight. Frozen samples were thawed overnight and mineralized N (NH_4^+ + NO_3^- + NO_2^-) was determined using a 2 *M* KCl extraction (Liegel et al., 1980) and analyzed using QuickChem Methods 12–107–04–1-B (NO_3^-) and 12–107–06–2-A (NH_4^+) on a Lachat automated N analyzer (Lachat Instruments, 1996).

Greenhouse Trial

The same soils and 12 of the 14 fecal types used in the incubations were used in a greenhouse trial (Table 3). Feces were added at a rate equivalent to 350 kg total N ha^{-1} and mixed thoroughly with 800 g of air-dried soil in four replicates. Quadruplet unamended controls for each soil type were also included. Phosphorus was applied at the rate of 40 kg P ha^{-1} as KH_2PO_4. Pots were watered every 2 to 3 d to maintain 60% WFPS and pots were relocated randomly twice weekly. After an initial 5-d fallow period, 10 oat (cv. Bay 97-ADP-101) seeds were planted, seedlings were thinned at 10 d to keep the five most robust plants, and after a 45-d growth period, shoots and roots were harvested. Soil and organic debris were washed from roots and wash water returned to pots. Roots were removed to minimize their impact on subsequent soil N mineralization and crop growth, and wash water returned to pots to return residual feces. Oat harvest was followed by a 20-d fallow period, after which sorghum (cv Pioneer 8313-N271) was planted and grown in the same manner as oats for 45 d. Sorghum shoots were harvested, and plants were allowed to ratoon for an additional 45 d. In total there were three crop-fallow cycles covering a 155-d period. Subsamples of shoots were dried, ground to pass a 1-mm sieve and the same procedures outlined for feces were used to determine DM and N contents.

Calculations and Statistics

Differences in soil IN, plant DM and N uptake due to treatments were calculated by subtracting the amount of soil IN, plant DM, and N uptake in unamended controls from amounts in fecal-amended incubation cups and greenhouse pots. Adjusted data were analyzed by generalized least squares analysis of variance, assuming blocks to be a random effect and fecal samples, soil types, time and all interactions to be fixed (SAS Institute, 1990). The model was a split-plot-in-time with fecal samples and soil types treated as one whole-plot factor and times treated as the other whole-plot factor (Steel et al., 1997). Soil type was split into two single-degree-of-freedom contrasts: silt loams vs. sandy loam and Plano vs. Loyal silt loams. The time factor was split into linear, quadratic, cubic, and residual terms, using orthogonal contrasts, although only the linear and quadratic components are reported due to their general significance levels. Regression models that best described changes in soil IN levels over the 365-d soil incubation trial, and also to evaluate relationships between the chemical composition of applied feces and measured soil IN, plant DM and N were fit based on the results from the orthogonal contrast analysis in the ANOVAs. Where relevant, the protected least significant difference (LSD) test was used to determine significant differences among treatments at $P < 0.05$.

RESULTS

Feces from different diets had somewhat narrow ranges of total C (439–474 g kg^{-1}), total N (24.4–32.3 g kg^{-1}), C/N ratios (11.7–18.3), NDF (501–599 g kg^{-1}), and undigested feed N (NDIN, 4.8–8.4 g kg^{-1}; Table 3). Highest concentrations of fecal total C, total N, and NDIN tended to come from cows fed CS-AS-AH diets, mid-range concentrations were associated with cows fed CP-F diets, and lowest concentrations came from cows fed CS-AS-CP diets. Feces from cows fed CP-F and CS-AS-CP diets had similar average NDF concentrations (553 g kg^{-1}), which were higher than average NDF contents (520 g kg^{-1}) of feces derived from CS-AS-AH diets.

Soil Incubations

Differences between soil IN extracted from the feces-amended and unamended soils were deemed due to effects of diet on chemical composition of feces and subsequent fecal N mineralization in soil. Positive soil IN values indicated net mineralization of applied fecal N, and negative values indicated that applied feces immobilized soil N. Positive or negative soil IN values were therefore dependant on soil IN levels in the non-amended controls. Over the first 14 d in the unamended controls, soil IN levels in the Rosholt soil were greater ($P < 0.05$) than soil IN levels in the Plano soils (Fig. 1). The Plano and the Loyal soils had similar soil IN levels during this initial 2-wk period. Although apparently different (Fig. 1), there were no significant ($P < 0.05$) differences in soils IN levels among the three soils at the 28, 56, 122, and 224 d sampling dates due to high soil IN variability within each soil type. Soil IN extracted from the Plano soil at 365 d was significantly ($P < 0.05$) greater than soil IN extracted from the Loyal or the Rosholt soils, which had similar soil IN at this sampling date.

In the feces-amended soils, soil type had the greatest impact on measured net soil IN, followed by fecal type and soil-by-feces interactions. Of total treatment variance, 33% was associated with net soil IN differences between the silt loams and the sandy loam, and an

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

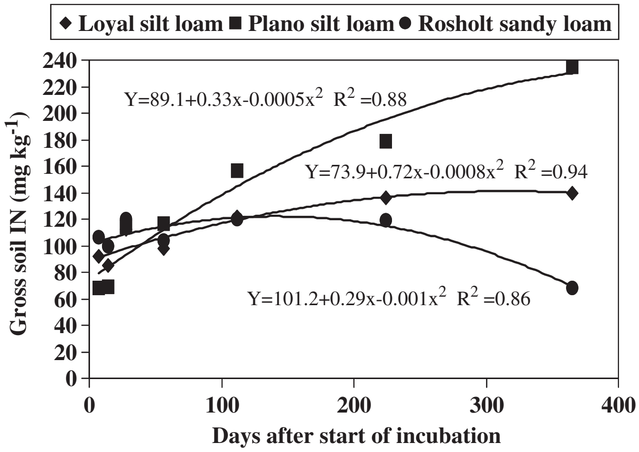

Fig. 1. Gross soil inorganic N in unamended soils.

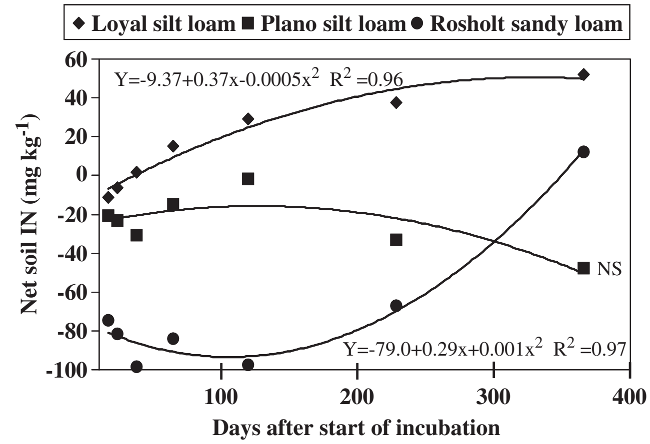

Fig. 2. Net inorganic N in soil amended with dairy feces from different diets.

additional 10% was associated with net soil IN differences between the silt loams (Table 4). Whereas feces application to the silt loams generally increased net soil IN (averaged over the 14 diets), feces application to the sandy loam caused net soil IN to decrease during the first 112 d, after which net soil IN increased rapidly (Fig. 2). Unlike the Loyal silt loam, the Plano silt loam soil displayed no significant ($P < 0.05$) relationship between feces application and net soil IN levels over the 365-d trial (Fig. 2). Perhaps the principal difference between the two silt loams in net soil IN levels was due to the very different soil IN levels in unamended controls (Fig. 1).

Feces-by-soil interactions accounted for approximately 17% of total treatment variability (Table 4). Whereas application of feces from cows fed CS-HP and CS-LP diets to the Loyal silt loam resulted in positive net soil IN levels, application of the same fecal types to the Rosholt sandy loam resulted in net negative soil IN concentrations throughout most of the study period (Fig. 3). Application of feces derived from the AS-LP and AS-HP diets produced similar net soil IN levels in the Loyal silt loam and Rosholt sandy loam. After application to the Plano silt loam, feces derived from HP diets (averaged across CS and AS) produced higher net soil IN than feces derived from LP. At trial's end, fecal type had significant effects on net soil IN levels in each of the three soil types. In the Loyal silt loam, net soil IN levels were lowest ($P < 0.05$) in incubation cups amended with feces derived from CS-LP. In the Plano silt loam, feces derived

Table 4. Partial ANOVA for fecal type, soil, and sampling day effects on net soil inorganic N (mg kg^{-1}).

Source	df	MS	P-value	Variation†
Fecal type (F)	13	28148	.0002	10.4
Silt loam vs. sandy loam (S1)	1	1147450	< .0001	32.7
Loyal silt loam vs. Plano silt loam (S2)	1	335299	< .0001	9.6
F × S1	13	14836	.0519	5.5
F × S2	13	29950	.0001	11.1
Whole-plot error	126	8302	< .0001	–
F × day linear (DL)	13	4060	< .0001	1.5
S1 × DL	1	149677	< .0001	4.3
S1 × day quadratic (DQ)	1	151280	< .0001	4.3
S2 × DL	1	165069	< .0001	4.7
F × S2 × DL	13	9312	< .0001	3.5
F × S2 × DQ	13	3145	.0004	1.2
Error	756	1088	–	–

† Percentage of total treatment variation (fecal samples, soil types, time, and all treatment interactions) attributable to each individual effect.

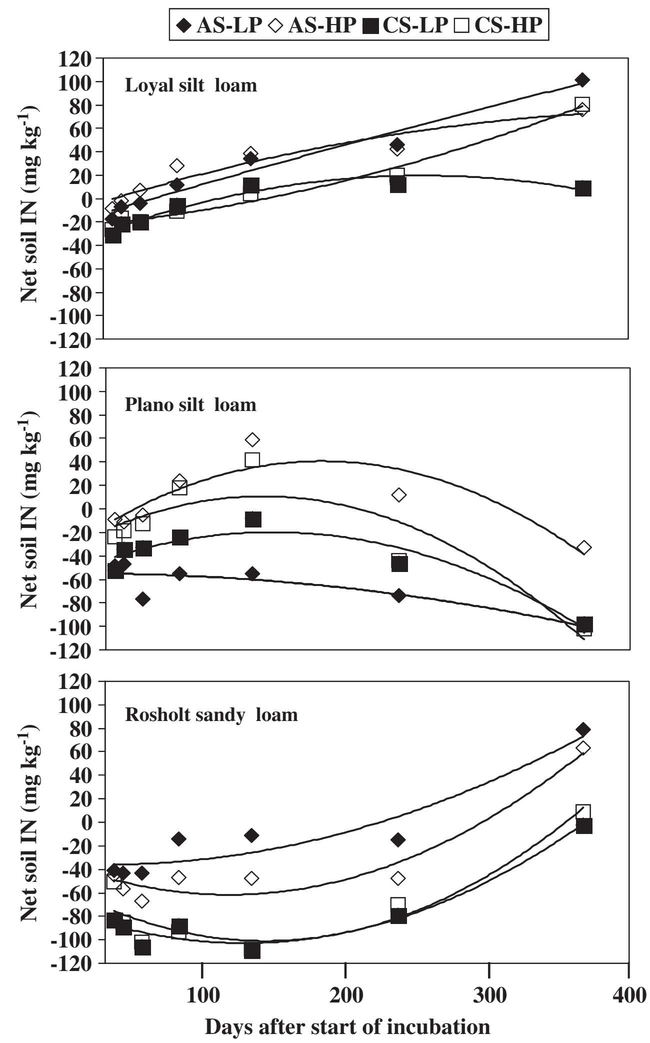

Fig. 3. Net inorganic N in soils amended with feces derived from alfalfa silage (AS), or corn silage (CS) diets fed at low (LP) or high (HP) crude protein levels.

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

from AS-HP had higher ($P < 0.05$) net soil IN levels than feces from other diets. In the Rosholt sandy loam, feces from AS diets averaged across CP levels produced greater ($P < 0.05$) net soil IN than feces from CS diets averaged across CP levels. Only in the Plano soil did diet CP level have an effect on net soil IN. In this soil, feces from the HP diets, averaged across CS and AS, had greater ($P < 0.05$) net soil IN levels than feces from LP diets at the 7, 14, 28, 56, and 112 d sampling dates (Fig. 4).

Feces from cows fed CS-AS-AH diets had different effects on soil IN. After application to the Rosholt sandy loam, the four fecal types derived from these diets all had similar patterns of soil IN formation, that is, an initial 112 d of N immobilization was followed by gradual N mineralization to 365 d (Fig. 5). After application to Loyal silt loam, all CS-AS-AH feces resulted in positive soil IN levels. After application to the Plano silt loam, however, feces derived from 100CS and especially 75CS-25AH produced negative soil IN (immobilization). At trials end in the Plano soil, feces derived from 75CS-25AH produced significantly ($P < 0.05$) lower soil IN levels than soils amended with other CS-AS-AH manure types.

Greenhouse Trial

Analysis of soil and fecal type impacts on plant DM production and N uptake over the three growing periods is shown in Table 5. Few significant interactions among treatments were detected and, when detected, accounted for a small fraction (<2%) of treatment variability. Therefore, discussion of treatment effects on plant DM and N uptake will relate to main soil and fecal type effects.

Similar to treatment effects in the incubation trial, plant DM production and especially N uptake were most affected by soil type, followed by fecal type. Approximately 30% of the variation in oat DM (Harvest 1) and 51% of the variation in sorghum DM (Harvest 2) could be attributed to soil type. Sorghum ratoon DM (Harvest 3) was similar across soil types. Average oat DM in pots containing the Loyal and Rosholt soils (1.2 g pot^{-1}) were similar, and significantly ($P < 0.05$) greater, than in pots containing the Plano soil (0.7 g pot^{-1}). Sorghum DM in pots containing Loyal and Plano soils were similar (2.9 g pot^{-1}) and significantly ($P < 0.05$) greater than sorghum DM in pots containing Rosholt soil (2.2 g pot^{-1}).

As observed with plant DM, soil type had the greatest impact on plant N uptake accounting for 67, 65, and 82% of the variability in N uptake by oats, sorghum and sorghum ratoon, respectively (Table 5). Oat N uptake in pots amended with feces from cows fed CP-F and CS-AS-AH diets were similar (15.5 mg pot^{-1}) and significantly ($P < 0.05$) greater than in pots amended with feces from cows fed the CS-AS-CP diets (11.1 mg pot^{-1}). The impact of feeding trial feces on sorghum and sorghum ratoon N uptake depended on soil type (Fig. 6). In the Loyal silt loam, sorghum N uptake in pots amended with feces from cows fed CS-AS-AH and CS-AS-CP diets were similar and significantly ($P < 0.05$) greater than sorghum N uptake in pots amended with feces derived from the CP-F feeding trial. This pattern changed, however, in the Plano silt loam and Rosholt

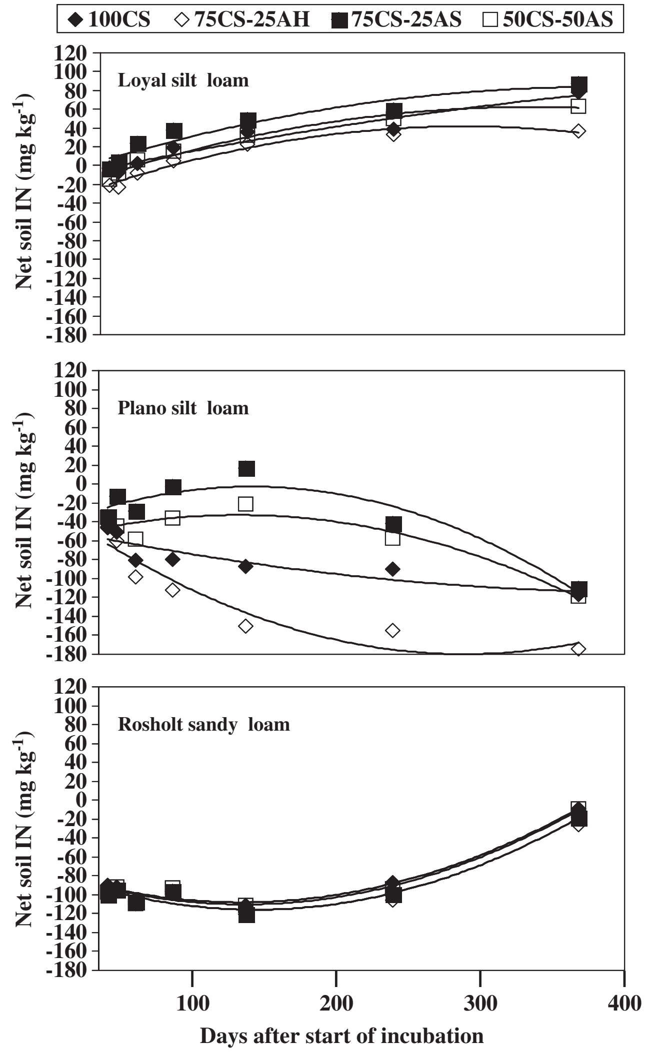

Fig. 5. Net inorganic N in soils amended with feces derived from alfalfa hay (AH), alfalfa silage (AS), or corn silage (CS) diets.

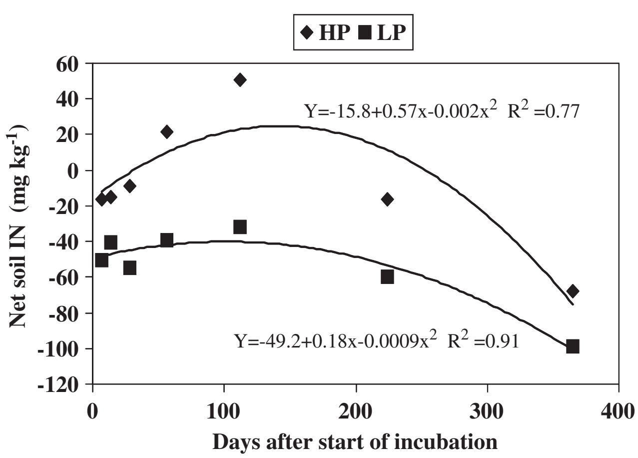

Fig. 4. Net inorganic N in Plano silt loam amended with feces from low (LP) or high (HP) crude protein diets (averaged across levels of AS and CS).

Table 5. Partial ANOVA for soil type, feeding trial, and feed component effects on crop dry matter (DM) yield and nitrogen (N) uptake.

		Crop DM, g pot^{-1}						Crop N uptake, mg pot^{-1}					
		Oats		Sorghum		Sorghum ratoon		Oats		Sorghum		Sorghum ratoon	
Source of variation†	df	*P*-value	%Trt.	*P*-value	%Trt.	*P*-value	%Trt.	*P*-value	%Trt.	*P*-value	%Trt.	*P*-value	%Trt.
Soil type (S)	2	<0.0001	30.1	<0.0001	50.7	NS	NS	<0.0001	66.6	<0.0001	64.8	<0.0001	82.2
Feeding trial (T)	2	0.0002	12.4	NS	NS	NS	NS	<0.0001	3.0	0.0018	4.7	0.0319	1.7
S × T	1	NS	–	NS	–	NS	NS	NS	NS	<0.0001	17.9	0.0004	5.5
LCP-MF vs. HCP-MF (B1)	1	0.0063	5.2	NS	NS	NS	NS	0.0007	2.2	NS	NS	NS	NS
AH vs. AS (M3)	1	NS	–	NS	–	NS	–	NS	–	0.0060	2.7	NS	–
AS vs. CS (WK1)	1	<0.0001	25.6	0.0247	6.7	NS	NS	<0.0001	15.9	NS	NS	NS	NS
LCP vs. HCP(WK2)	1	0.0516	2.6	0.0689	4.4	NS	NS	NS	–	NS	–	0.0425	1.0

† See Table 2 for description of feeding trials and feed components. B1 = feces from LCP vs. HCP averaged across medium fiber (MF) level; M3 = feces from alfalfa silage (AS) vs. alfalfa hay (AH) when either comprised 25% of forage DM; WK1 = feces from corn silage (CS) vs. AS averaged across crude protein (CP) levels; WK2 = feces from LCP vs. HCP averaged across CS and AS.

sandy loam where sorghum N uptake was greater ($P < 0.05$) in pots amended with CP-F feces than in pots amended with feces from the CS-AS-AH and CS-AS-CP diets. Also in the Plano silt loam, feces derived from the CP-F and CS-AS-CP diets resulted in greater ($P < 0.05$) N uptake by sorghum ratoon than feces derived from the CS-AS-AH diets.

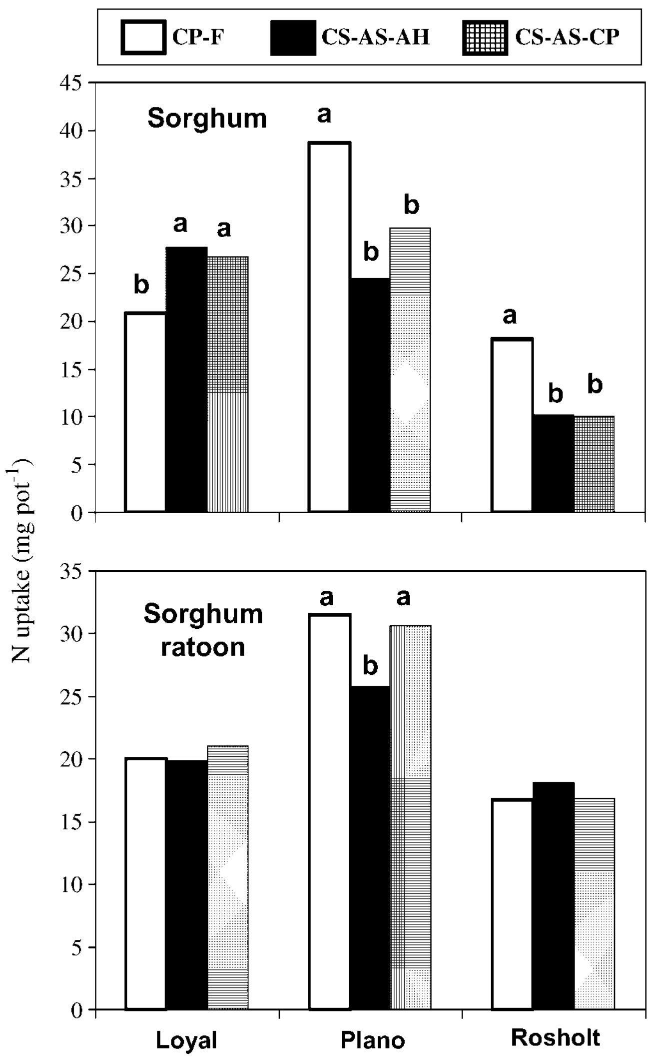

Fig. 6. Nitrogen uptake by sorghum in Plano, Loyal and Rosholt soils amended with feces from three feeding trials (within a soil type, sorghum, or sorghum ratoon, bars with different letters have significantly [$P < 0.05$] different N uptakes).

Feeding trial effects on plant DM production and N uptake can be further explained by the impact of specific diet components. For example, oat and sorghum DM, and oat N uptake were significantly greater in pots amended with feces from AS than in pots amended with feces from CS (both averaged across soil types and CP levels in the CS-AS-CP trial; Fig. 7). Also, application of feces from high dietary CP (averaged across soil types and fiber levels) significantly increased oat DM and N uptake compared with the application of feces from low levels of dietary CP (Fig. 8). Two additional significant ($P < 0.05$) effects of dietary CP were observed (Table 5); feces derived from low CP diets averaged over CS and AS levels (1) reduced oat DM, but had no effect on oat N uptake, and (2) reduced N uptake of sorghum ratoon (data not shown). Feces derived from different levels of dietary F produced only one impact; sorghum ratoon N uptake was significantly ($P < 0.05$) greater in pots amended with feces derived from high fiber diets (averaged over dietary CP) than in pots amended with feces derived from low fiber diets (data not shown).

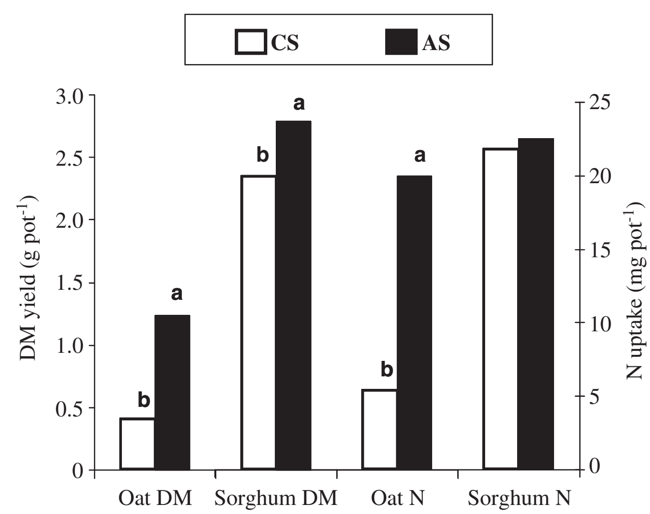

Fig. 7. Plant yield and N uptake in soils (averaged across three soil types) amended with feces from alfalfa silage (AS) or corn silage (CS) diets (averaged across levels of dietary CP). (within a forage type, bars with different letters have significantly [$P < 0.05$] different DM or N uptakes).

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

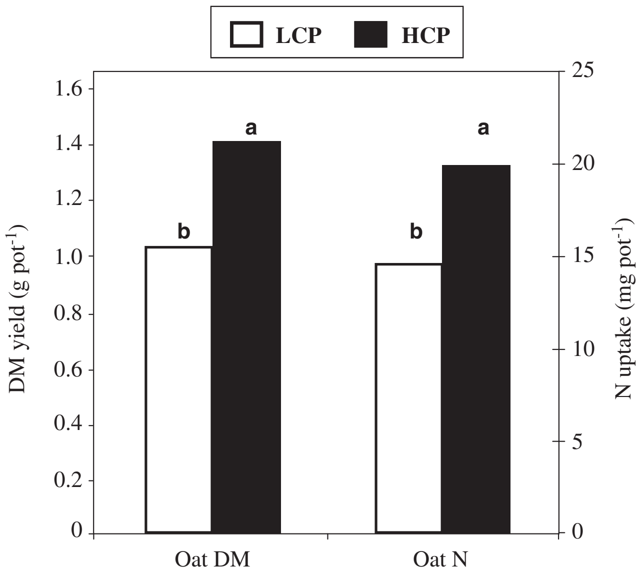

Fig. 8. Oat yield and N uptake in soils (averaged across three soil types) amended with feces from low (LCP) or high (HCP) crude protein diets (averaged across levels of dietary fiber). (bars with different letters have significantly [$P < 0.05$] different DM or N uptake).

Relationships between Fecal Chemical Properties, Soil Inorganic Nitrogen, and Plant Response

Few significant relationships were found among the chemical properties of applied feces (Table 3) and subsequent soil IN, plant DM, and N uptake. In the Plano and Rosholt silt loams, no relationships were found between any fecal chemical property and soil IN levels over the 365 d incubation trial. In the Loyal soil, significant relationships between the N content or C/N ratio of applied feces and soil IN levels were detected at sample Days 28, 56, 112, and 224. At these four sampling dates, fecal N accounted for 42 to 56% of the variability in soil IN measurements (i.e., linear regression R^2 of 0.42 to 0.56) and fecal C/N ratio accounted for 42 to 65% of the variability in soil IN measurements. Soil IN levels measured at the 224 d sampling date were also related ($P < 0.05$, $R^2 = 0.56$) to the undigested feed N in feces, indicating mineralization of this recalcitrant manure N fraction occurred during the latter stages of the incubation trial. In the greenhouse trial, the C/N ratio of feces was found to be a significant ($P < 0.05$) predictor of plant DM and N uptake, depending on soil type. Significant ($P < 0.05$) negative linear relationships were determined between C/N ratio of applied feces and sorghum DM yield ($R^2 = 0.55$) in the Loyal soil; oat DM yield ($R^2 = 0.51$) and oat N uptake ($R^2 = 0.30$) in the Plano soil; and oat DM yield ($R^2 = 0.37$), oat N uptake ($R^2 = 0.76$), sorghum DM yield ($R^2 = 0.34$) and sorghum N uptake ($R^2 = 0.25$) in the Rosholt soil.

DISCUSSION

The three soils used in this study had a wide range of soil textures and chemical properties (Table 1), which had the greatest impact on soil N mineralization (Table 4), crop yield and N uptake (Table 5). Under normal climatic and soil management conditions, agricultural soils in Wisconsin annually mineralize approximately 2.5% of total soil N (Vanotti et al., 1997). At this mineralization rate, annual soil IN productions of approximately 53, 51, and 22 mg kg^{-1} could be expected for the Loyal, Plano, and Rosholt soils, respectively. However, the unamended controls had average soil IN values of 140, 235, and 68 mg kg^{-1} (Fig. 1), or some three to five times greater than what would be expected under field conditions. Reasons for high soil IN levels in unamended controls likely were associated with multiple factors, including (1) the drying, sieving, and rewetting of our soils, and their incubation at ideal temperature and moisture likely enhanced initial soil IN formation, and (2) the non-addition of an organic amendment may have disrupted soil organic matter dynamics resulting in higher soil IN formation than under normal soil management practices. When heterotrophic microbial communities are deprived of normally supplied organic C inputs, biologically active pools of soil organic matter (SOM) decline (Franzluebbers, 2004). This can lead to a net release of soil nutrients (Powell and Hons, 1991; Seiter and Horwath, 2004), which could have occurred during the 365-d incubation period in unamended control soils.

Two of the three feeding trials from which feces for the present study were derived determined that high dietary CP levels did not significantly ($P < 0.05$) impact milk production or composition, but altered the relative excretion of manure N in urine and feces. The feeding trial (Broderick, 2003) that examined interactive effects of dietary CP and F levels determined that an increase (from 15.1 to 18.4%) in dietary CP decreased (from 31 to 25% of N intake) the relative amount of consumed dietary N converted to milk, and increased (from 23 to 35% of N intake) the relative excretion of N in urine. Misselbrook et al. (2005) found that an increase in dietary CP from 13.6 to 19.4% of dietary DM not only increased urine N excretion but also ammonia emissions after slurry application to soil. In the present study, the feces derived from this trial had no discernable impacts on soil IN levels. Feces from the LCP diets, however, decreased oat DM production and N uptake (Fig. 8), an effect that may be overcome with the addition of a small amount of fertilizer N, or additional manure N.

The feeding trial (Wattiaux and Karg, 2004a, 2004b) that examined interactive effects of forage type (CS or AS) and dietary CP found that cows fed CS-based diets produced more milk but lower percentage of milk fat than cows fed AS-based diets, and had significantly less total (urinary plus fecal) N excretions and more N excreted in feces than cows fed AS-based diets. Also from this trial, cows fed HCP (17.8%) excreted significantly higher amounts of urinary N, than cows fed LCP (16.7%). After application to soil, feces from cows fed CS-based diets generally had lower soil IN levels, especially in soils amended with feces from the CS-LP diet, than soils amended with feces from AS-based (Fig. 3). After application to the Plano soil, feces from cows fed HP resulted in higher soil IN levels than feces

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

from cows fed LP (Fig. 4). Feces from AS-based diets increased both oat and sorghum DM production and oat N uptake (Fig. 7).

The feeding trial (Moreira et al., 1999) that varied levels of AS and CS, and replaced AS with AH, determined that cows fed diets containing all CS as the forage component produced less milk than cows fed two levels of AS (75%CS-25%AS and 50%CS-50%AS). Milk production from cows fed 75%CS-25%AH was significantly ($P < 0.05$) less than from cows fed other diets. In the present study, significant ($P < 0.05$) reductions in soil IN levels (Fig. 5) and sorghum N uptake (Table 5) were determined in soils amended with feces derived from the diet that replaced AS with AH. Brito and Broderick (2003) found that an equal mix of AS and CS maximized N secretion in milk, compared with diets dominated by either one of these forages. These results indicate that a balance of alfalfa and corn in the cropping system would be needed to not only optimize milk production, but also the economic and environmental performance of dairy farms.

Differences in oat N uptake were likely due to differences in soil IN due to soil type during the initial stages of the trial. Whereas highest oat N uptake occurred in the Rosholt sandy loam having a relatively low level total soil N, lowest oat N uptake occurred in the Plano silt loam with a relatively high level of total soil N (Table 1). The different physical and chemical characteristics of the three soils used in this study likely impacted soil microbial populations, which in turn impacted observed patterns of N mineralization, especially in the unmended control incubation cups, and crop response. Of the total manure N applied to the Loyal soil, approximately 10, 18, and 15% was taken up by oats, sorghum and sorghum ratoon, respectively. Comparative relative plant N uptake values for the Plano soil were 4, 20, and 21%, and for the Rosholt soil, 22, 11, and 12%, respectively. Total apparent plant N uptake of applied manure N was similar ($P < 0.05$) between the Loyal (43%), Plano (45%), and Rosholt (45%) soils. Most applied fecal N not taken up by plants likely remained in soil. Dairy feces contained negligible amounts of ammonium N (data not shown), so no fecal N was likely converted and lost via ammonia volatilization. Non-draining pots were used in the greenhouse trial, so there were no losses of nitrate N. Incubated and greenhouse soils were maintained at optimum moisture, so negligible fecal N was likely loss via denitrification. Even under ideal conditions denitrification losses range from 0.2 to 7.1% of incorporated dairy manure N (Dittert et al., 1998).

The feces applied to soil in the present study had a fairly narrow range of C/N ratios (11.7–18.3; Table 3), within which one would have expected net positive soil IN after application to soil. Calderón et al. (2004) found that although most incubated dairy manure ($n = 107$) initially immobilized N, patterns of soil IN were related to the C/N ratio of manures. Manures with C/N ratios of ≥19 caused immobilization of soil N, whereas manure having average C/N ratios of ≤16 mineralized N. Within a C/N ratio range of 6 to 13, Sørensen et al. (2003) determined a negative relationship between C/N ratios of dairy slurries and slurry N mineralization in soil. Heal et al. (1997) found that whereas organic materials having C/N ratios <20 decompose rapidly in soils; C forms can highly influence decomposition and N mineralization. More detailed analyses of the C compounds (e.g., hemicellulose, cellulose, lignin), or secondary compounds (e.g., tannins, polyphenolics; Somda et al., 1995) contained in feces could perhaps more fully describe the impacts of fecal chemical composition on fecal N mineralization in soil.

An improved understanding of impact of dairy diet on manure N composition and transformation in soil may assist in various short- and long-term management decisions. Over the short term, better predictions of manure N mineralization and plant availability may be made. The long-term impacts, such as soil N accumulation and associated hazards of NO_3^- leaching and denitrification, sequestration of C in soil, and impacts (e.g., fertilizer use and soil erosion) of the cropping systems designed to provide diet components (e.g., alfalfa vs. corn grain or silage) may be most important (Magdoff and Weil, 2004). For example, differential mineralization of fecal N due to diet could enhance N uptake by crops and decrease NO_3^- losses from cropland. These shifts may either improve uptake of crop N by improving synchronization of supply (Russelle and Hargrove, 1989), increase the predictability of N availability in a crop rotation, and play an important role in soil C sequestration. Long-term repeated applications of dairy manure derived from different diets could be more pronounced than this study's short-term impacts observed during 365-d incubation and 155-d greenhouse trial that followed a single manure application.

CONCLUSIONS

This study determined that dietary forage and CP levels impact fecal chemical composition, fecal N mineralization, plant yield, and N uptake. Although field conditions and results would perhaps be different than the soil-manure incubations and greenhouse conditions, there are potential broad implications of these results. For example, alfalfa and corn have very different impacts (e.g., N fixation, soil erosion) when grown in the field and fed to dairy cows. Our joint trials demonstrated that feeding alfalfa rather than corn silage to dairy cows enhanced milk production and composition, and provided manure which in some soils (i) mineralized N in a pattern that coincided with crop N demands, as demonstrated in the incubation study, and (ii) produced higher crop yield and N uptake, as shown in the greenhouse trial. A somewhat similar analogy can be made for dietary CP. If not fed excessively, protein supplements enhanced milk production and composition, provided manure that became more readily available for crop uptake, and increased crop yield and N uptake. As farmers seek to provide least-cost rations to their dairy cows, perhaps dual economic and environmental goals can be achieved. Dairy cows may be fed a mix of diet components that not only maintain high levels of milk

Reproduced from Soil Science Society of America Journal. Published by Soil Science Society of America. All copyrights reserved.

production, but also produce excreta with enhanced nutrient cycling characteristics after application to soil.

REFERENCES

Brito, A.F., and G.A. Broderick. 2003. Effects of different dietary ratios of alfalfa and corn silage on milk production and rumen metabolism in lactating dairy cows. J. Dairy Sci. 86(Suppl. 1):62.

Broderick, G.A. 2003. Effects of varying dietary protein and energy levels on the production of lactating dairy cows. J. Dairy Sci. 86:1370–1381.

Calderón, F.J., G.W. McCarty, J.S. Van Kessel, and J.B. Reeves, III. 2004. Carbon and Nitrogen dynamics during incubation of manured soil. Soil Sci. Soc. Am. J. 68:1592–1599.

Dittert, K., T. Goerges, and B. Sattelmacher. 1998. Nitrogen turnover in soil after application of animal manure and slurry as studied by the stable isotopes 15N: A review. Z. Pflanzenernahr. Bodenk. 161:453–463.

Franzluebbers, A.J. 2004. Tillage and residue management effects on soil organic matter. p. 227–268. In. F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Goering, H.K., and P.J. Van Soest. 1970. Forage fiber analysis (Apparatus, reagents, procedures, and some applications). Agric. Handb. No. 379. U.S. Gov. Print. Office, Washington, DC.

Heal, O.W., J.M. Anderson, and M.J. Swift. 1997. Plant litter quality and decomposition: An historic overview. p. 3–32. *In* G. Cadisch and K.E. Giller (ed.) Driven by nature: Plant litter quality and decomposition. CAB International. Wallingford, UK.

Lachat Instruments. 1996. Determination of total Kjeldahl in nitrogen in soils and plants by flow injection analysis. QuickChem Method 13–107–06–2-D. Lachat Instruments, Milwaukee, WI.

Liegel, E.A., C.R. Simson, and E.E. Schulte. 1980. Wisconsin procedures for soil testing, plant analysis and feed and forage analysis. Soil fertility. Series No. 6 (revised). University of Wisconsin, Madison, WI.

Magdoff, F., and R.R. Weil. 2004. Significance of soil organic matter to soil quality and health. p. 1–44. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Mason, V.C., and W. Frederiksen. 1979. Partitioning of nitrogen in sheep faeces with detergent solutions, and its application to the estimation of the true digestibility of dietary nitrogen and the excretion of non dietary faecal nitrogen. Zeitschrift fur Tierphysiologie, Tierernährung and futtermittelkkunde 41:121–131.

Misselbrook, T.H., J.M. Powell, G.A. Broderick, and J.H. Grabber. 2005. Dietary manipulation in dairy cattle: Laboratory experiments to assess the influence on ammonia emissions. J. Dairy Sci. 88:1765–1777.

Moreira, V.R., C.V. Cragnolino, and L.D. Satter. 1999. High corn silage diets for lactating dairy cows. p. 64–65. U.S. Dairy Forage Research Center 1999 Research Report. U.S. Dairy Forage Research Center, Madison, WI.

Powell, J.M., and F.M. Hons. 1991. Sorghum stover removal effects on soil organic matter content, extractable nutrients, and crop yield. J. Sust. Agric. 2:25–39.

Powell, J.M., F.N. Ikpe, and Z.C. Somda. 1999. Crop yield and fate of nitrogen and phosphorus after application of plant material or feces to soil. Nutr. Cycling Agroecosyst. 52:215–226.

Russelle, M.P., and W.L. Hargrove. 1989. Cropping systems: Ecology and management. p. 277–317. *In* R.F. Follett (ed.) Nitrogen management and ground water protection. Elsevier, Amsterdam.

SAS Institute. 1990. SAS/Stat user's guide. Version 6. SAS Institute Inc., Cary, NC.

Satter, L.D., T.J. Klopfenstein, G.E. Erickson, and J.M. Powell. 2005. Phosphorus and dairy-beef nutrition. p. 587–606. *In* A.N. Sharply, and J. T. Sims (ed.) Phosphorus agriculture and the environment. ASA-CSSA-SSSA Monogr. No. 46. ASA, CSSA, and SSSA, Madison, WI.

Seiter, S., and W.R. Horwath. 2004. Strategies for managing soil organic matter to supply plant nutrients. p. 269–294. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Somda, Z.C., J.M. Powell, S. Fernández-Rivera, and J.D. Reed. 1995. Feed factors affecting nutrient excretion by ruminants and fate of nutrients when applied to soil. p. 227–246. *In* J.M. Powell et al. (ed.) Livestock and sustainable nutrient cycles in mixed-farming systems of Sub-Sahara Africa. Volume II: Technical Papers, Proceeding of an International Conference held in Addis Ababa, Ethiopia, 22–26 Nov. 1993. ILCA International Livestock Center for Africa (ILCA), Addis Ababa, Ethiopia.

Sørensen, P., E.S. Jensen, and N.E. Nielsen. 1994. Labeling of animal manure nitrogen with 15N. Plant Soil 162:31–37.

Sørensen, P., M.R. Weisbjerg, and P. Lund. 2003. Dietary effects on the composition and plant utilization of nitrogen in dairy cattle manure. J. Agric. Sci. 141:79–91.

SPALS. 2004. Soil, Plant Analysis Laboratory Services. Procedures for soil testing, plant analysis and feed & forage analysis. Available online at http://uwlab.soils.wisc.edu/procedures.htm (verified 20 Jan. 2006). University of Wisconsin-Madison, WI.

Steel, R.G.D., J.H. Torrie, and D.A. Dickey. 1997. Principles and procedures of statistics: A biometrical approach. 3rd ed. McGraw-Hill Book Co., New York.

Van Horn, H.H., G.L. Newton, R.A. Norstedt, G. Kidder, E.C. French, D.A. Graetz, and C.F. Chambliss. 1996. Dairy manure management: Strategies for recycling nutrients to recover fertilizer value and avoid environmental pollution. Circ.1016 (revised) Florida Coop. Ext. Serv., Gainesville, FL.

Van Kessel, J.S., and J.B. Reeves. 2002. Nitrogen mineralization potential of dairy manures and its relationship to composition. Biol. Fertil. Soil 36:118–123.

Vanotti, M.B., L.G. Bundy, and A.E. Peterson. 1997. Nitrogen fertilizer and legume-cereal rotation effects on soil productivity and SOM dynamics in WI. p. 105–120. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Wattiaux, M.A., and K.L. Karg. 2004a. Protein level for alfalfa and corn silage-based diets: II. Nitrogen balance and manure characteristics. J. Dairy Sci. 87:3492–3502.

Wattiaux, M.A., and K.L. Karg. 2004b. Protein level for alfalfa and corn silage-based diets: I. Lactational responses and milk urea nitrogen. J. Dairy Sci. 87:3480–3491.